

Technology Characterization: Fuel Cells

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Technology Characterization – Fuel Cell Systems

Introduction and Summary

Fuel cell systems, currently in the early stages of development, are an entirely different approach to the production of electricity than traditional prime mover technologies. Fuel cells are similar to batteries in that both produce a direct current (DC) through an electrochemical process without direct combustion of a fuel source. However, whereas a battery delivers power from a finite amount of stored energy, fuel cells can operate indefinitely provided the availability of a continuous fuel source. Two electrodes (a cathode and anode) pass charged ions in an electrolyte to generate electricity and heat. A catalyst enhances the process.

Fuel cells offer the potential for clean, quiet, and efficient power generation. As with most new technologies, fuel cell systems face a number of formidable market entry issues resulting from product immaturity, over-engineered system complexities, and unproven product durability and reliability. These translate into high capital cost, lack of support infrastructure, and technical risk for early adopters. However, the many advantages of fuel cells suggest that they could well become the prime mover of choice for certain applications and products in the future.

The inventor of fuel cell technology is Sir William Grove, who demonstrated a hydrogen fuel cell in London in the 1830s. Grove's technology remained without a practical application for 100 years. Fuel cells returned to the laboratory in the 1950s when the United States space program required the development of new power systems. Today, the topic of fuel cells encompasses a broad range of different technologies, technical issues, and market dynamics that make for a complex but potentially promising outlook. Significant amounts of public and private investment are being applied to the development of fuel cell products for both stationary and transportation applications.

There are five types of fuel cells under development. These are: 1) phosphoric acid (PAFC), 2) proton exchange membrane (PEMFC), 3) molten carbonate (MCFC), 4) solid oxide (SOFC), and 5) alkaline (AFC). The electrolyte and operating temperatures distinguish each type. Operating temperatures range from near ambient to 1,800°F, and electrical generating efficiencies range from 30 to over 50% HHV.¹ As a result, they can have different performance characteristics, advantages and limitations, and therefore will be suited to distributed generation applications in a variety of approaches.

The different fuel cell types share certain important characteristics. First, fuel cells are not Carnot cycle (thermal energy based) engines. Instead, they use an electrochemical or battery-like process to convert the chemical energy of hydrogen into water and electricity and can achieve high electrical efficiencies. The second shared feature is that they use hydrogen as their

¹Most of the efficiencies quoted in this report are based on higher heating value (HHV), which includes the heat of condensation of the water vapor in the products. In engineering and scientific literature the lower heating value (LHV – which does not include the heat of condensation of the water vapor in the products) is often used. The HHV is greater than the LHV by approximately 10% with natural gas as the fuel (i.e., 50% LHV versus 45% HHV).

fuel, which is typically derived from a hydrocarbon fuel such as natural gas. Third, each fuel cell system is composed of three primary subsystems: 1) the fuel cell stack that generates direct current electricity; 2) the fuel processor that converts the natural gas into a hydrogen-rich feed stream; and 3) the power conditioner that processes the electric energy into alternating current or regulated direct current. Finally, all types of fuel cells have low emissions profiles. This is because the only combustion processes are the reforming of natural gas or other fuels to produce hydrogen and the burning of a low energy hydrogen exhaust stream that is used to provide heat to the fuel processor.

Today, there are only two commercially available fuel cells, a 200 kW PAFC unit² and a 250 kW MCFC unit.³ With over 200 units sold, the PAFC fleet has achieved over 5 million operating hours in a variety of distributed generation applications. These range from a New York City police station to a major postal facility in Alaska and a credit card processing system in Nebraska. Located in over 15 countries, this initial commercial fuel cell product has successfully introduced the capabilities and features of fuel cells into the distributed generation marketplace. The MCFC fleet is more limited, with half a dozen commercial units, but several more in the development stages. While nearly two dozen companies are currently field testing a variety of alternative fuel cell systems for market entry, the availability of a wide array of off-the-shelf, fully warranted fuel cell systems designed for broad customer classes is still several years away.

Applications

Fuel cell systems are envisioned to serve a variety of distributed generation applications and markets. Since all fuel cells are in an early stage of development, there is limited experience to validate those applications considered most competitive for fuel cells. This early stage of development and commercial use causes fuel cells to be high in capital cost and to have a higher project risk due to unproven durability and reliability. These two characteristics will force introductory fuel cell products into specific markets and applications that are most tolerant of risk due to other market or operational drivers.

In DG markets, the primary characteristic driving early market acceptance is the ability of fuel cell systems to provide reliable premium power. The primary interest drivers have been their ability to achieve high efficiencies over a broad load profile and low emission signatures without additional controls.

Potential DG applications for fuel cell systems include combined heat and power (CHP), premium power, remote power, grid support, and a variety of specialty applications. **Figure 1** illustrates two actual sites with fuel cell systems functioning in DG applications.

² Sold by UTC Fuel Cells as the PC25, www.utcfuelcells.com.

³ Sold by FuelCell Energy as the DFC[®] 300, www.fce.com.

Figure 1. FuelCell Energy Molten Carbonate Fuel Cells in Distributed Generation



Applications

Source: www.fuelcells.org/pics.

Combined Heat and Power

Due to the high installed cost of fuel cell systems, the most prevalent DG application envisioned by product development leaders is CHP. CHP applications are on-site power generation in combination with the recovery and use of by-product heat. Continuous baseload operation and the effective use of the thermal energy contained in the exhaust gas and cooling subsystems enhance the economics of on-site generation applications.

Heat is generally recovered in the form of hot water or low-pressure steam (<30 psig), but the quality of heat is dependent on the type of fuel cell and its operating temperature. The one exception to this is the PEM fuel cell, which operates at temperatures below 200°F, and therefore has only low quality heat. Generally, the heat recovered from fuel cell CHP systems is appropriate for low temperature process needs, space heating, and potable water heating. In the case of SOFC and MCFC technologies, medium pressure steam (up to about 150 psig) can be generated from the fuel cell's high temperature exhaust gas, but the primary use of this hot exhaust gas is in recuperative heat exchange with the inlet process gases.

The simplest thermal load to supply is hot water. Primary applications for CHP in the commercial/institutional sectors are those building types with relatively high and coincident electric and hot water/space heating demand such as colleges and universities, hospitals and nursing homes, and lodging. Technology developments in heat activated cooling/refrigeration and thermally regenerated desiccants will enhance fuel cell CHP applications by increasing the thermal energy loads in certain building types. Use of these advanced technologies in applications such as restaurants, supermarkets, and refrigerated warehouses provides a base-thermal load that opens these applications to CHP.

Premium Power

Consumers who require higher levels of reliability or power quality, and are willing to pay for it, often find some form of DG to be advantageous. These consumers are typically less concerned about the initial prices of power generating equipment than other types of consumers. Premium power systems generally supply base load demand. As a result, and in contrast to back-up generators, emissions and efficiency become more significant decision criteria.

Fuel cell systems offer a number of intrinsic features that make them suitable for the premium power market. These market-driving features include low emissions/vibration/noise, high availability, good power quality, and compatibility with zoning restrictions. As emissions become more relevant to a business's bottom line in the form of zoning issues and emissions credits, the fuel cell becomes a more appealing type of DG.

Some types of fuel cell systems have already demonstrated high availability and reliability. As fuel cells further mature in the market, they are expected to achieve the high reliability associated with fewer moving parts.

While the fuel cell requires significant power conditioning equipment in the form of direct current to alternating current conversion, power from fuel cell systems is clean, exhibiting none of the signal disturbances observed from grid sources.

Finally, zoning issues for fuel cell systems are quite possibly the least problematic of all DG systems. Fuel cell systems can be designed for both indoor and outdoor installation, and in close proximity to sensitive environments, people, or animals.

Remote Power

In locations where power from the local grid is unavailable or extremely expensive to install, DG is a competitive option. As with premium power, remote power applications are generally base load operations. Consequently, emissions and efficiency become more significant criteria in much of the remote power DG market. Coupled with their other potential advantages, fuel cell systems can provide competitive energy into certain segments of the remote power DG market. Where fuel delivery is problematic, the high efficiency of fuel cell systems can also be a significant advantage.

Grid Support

One of the first applications that drew the attention of electric utilities to fuel cell technologies was grid support. Numerous examples of utility-owned and operated distributed generating systems exist in the U.S. and abroad. The primary application in the U.S. has been the use of relatively large diesel or natural gas engines for peaking or intermediate load service at municipal utilities and electric cooperatives. These units provide incremental peaking capacity and grid support for utilities at substations. Such installations can defer the need for T&D system expansion, can provide temporary peaking capacity within constrained areas, or be used for system power factor correction and voltage support, thereby reducing costs for both

customers and the utility system. The unique feature of fuel cell systems is the use of power conditioning inverters to transform direct current electricity into alternating current. These power conditioners can be operated almost independent of the fuel cell to correct power factors and harmonic characteristics in support of the grid.

Standby Power

Fire and safety codes require standby power systems for hospitals, elevator loads, and water pumping. Standby is an economic choice for customers with high outage costs such as those in the telecommunications, retail, gaming, banking, and certain process industries. The standby engine-driven generator set is typically the simplest distributed generation system, providing power only when the primary source is out of service or falters in its voltage or frequency. This application requires low capital cost, minimal installation costs, rapid black start capability, onsite fuel storage, and grid-isolated operation. In standby power applications, efficiency, emissions, and variable maintenance costs are usually not major factors in technology selection. Based on this definition of standby power, fuel cells do not appear to have much application. Fuel cell systems are characteristically high in capital cost and do not have rapid black start capability.

Peak Shaving

In certain areas of the country, customers and utilities are using on-site power generation to reduce the need for costly peak-load power. Peak shaving is also applicable to customers with poor load factor and/or high demand charges. Typically, peak shaving does not involve heat recovery, but heat recovery may be warranted where the peak period is more than 2,000 hours/year. Since low equipment cost and high reliability are the primary requirements, equipment such as reciprocating engines are ideal for many peak-shaving applications. Emissions may be an issue if operating hours are high. Combining peak shaving and another function, such as standby power, enhances the economics. High capital cost and relatively long start-up times (particularly for MCFC and SOFC) will most likely prevent the widespread use of fuel cells in peak shaving applications.

Technology Description

Fuel cells produce direct current electricity through an electrochemical process, much like a standard battery. Unlike a standard battery, a fuel supply continuously replenishes the fuel cell. The reactants, most typically hydrogen and oxygen gas, are fed into the fuel cell reactor, and power is generated as long as these reactants are supplied. The hydrogen (H_2) is typically generated from a hydrocarbon fuel such as natural gas or LPG, and the oxygen (O_2) is from ambient air.

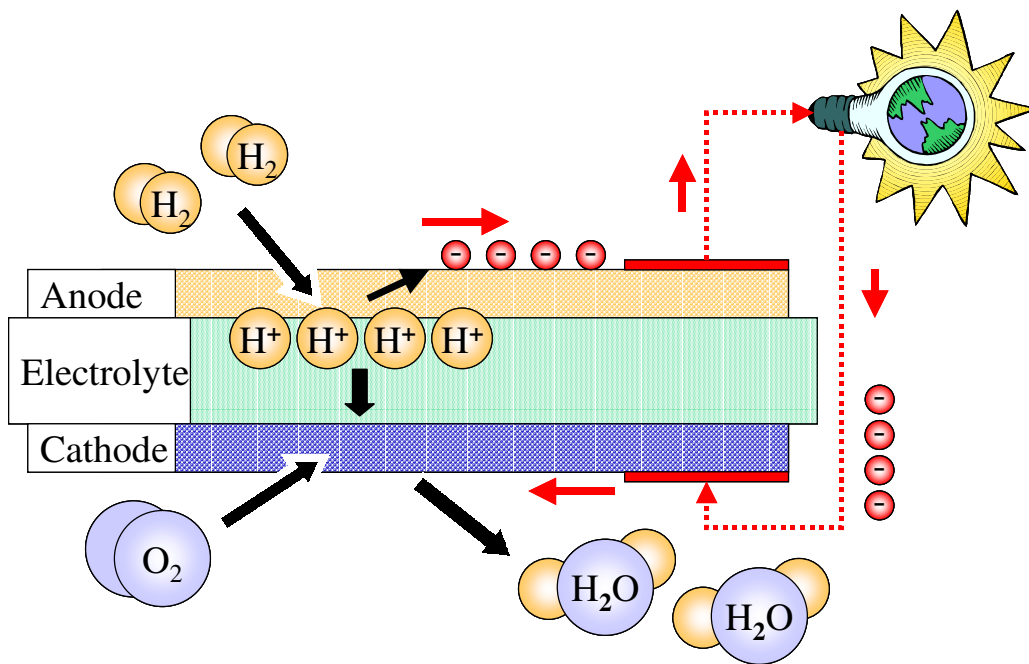
Basic Processes and Components

Fuel cell systems designed for DG applications are primarily natural gas or LPG fueled systems. Each fuel cell system consists of three primary subsystems: 1) the fuel cell stack that generates direct current electricity; 2) the fuel processor that converts the natural gas into a hydrogen rich

feed stream; and 3) the power conditioner that processes the electric energy into alternating current or regulated direct current.

Figure 2 illustrates the electrochemical process in a typical single cell, acid-type fuel cell. A fuel cell consists of a cathode (positively charged electrode), an anode (negatively charged electrode), an electrolyte and an external load. The anode provides an interface between the fuel and the electrolyte, catalyzes the fuel reaction, and provides a path through which free electrons conduct to the load via the external circuit. The cathode provides an interface between the oxygen and the electrolyte, catalyzes the oxygen reaction, and provides a path through which free electrons conduct from the load to the oxygen electrode via the external circuit. The electrolyte, an ionic conductive (non-electrically conductive) medium, acts as the separator between hydrogen and oxygen to prevent mixing and the resultant direct combustion. It completes the electrical circuit of transporting ions between the electrodes.

Figure 2. Fuel Cell Electrochemical Process



Source: Energy Nexus Group.

The hydrogen and oxygen are fed to the anode and cathode, respectively. The hydrogen and oxygen gases do not directly mix and combustion does not occur. Instead, the hydrogen oxidizes one molecule at a time, in the presence of a catalyst. Because the reaction is controlled at the molecular level, there is no opportunity for the formation of NO_x and other pollutants.

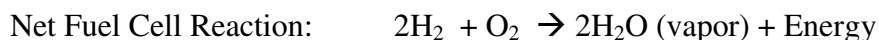
At the anode the hydrogen gas is electrochemically dissociated (in the presence of a catalyst) into hydrogen ions (H⁺) and free electrons (e⁻).



The electrons flow out of the anode through an external electrical circuit. The hydrogen ions flow into the electrolyte layer and eventually to the cathode, driven by both concentration and potential forces. At the cathode the oxygen gas is electrochemically combined (in the presence of a catalyst) with the hydrogen ions and free electrons to generate water.



The overall reaction in a fuel cell is as follows:



The amount of energy released is equal to the difference between the Gibbs free energy of the product and the Gibbs free energy of the reactants.

When generating power, electrons flow through the external circuit, ions flow through the electrolyte layer and chemicals flow into and out of the electrodes. Each process has natural resistances, and overcoming these reduces the operational cell voltage below the theoretical potential. There are also irreversibilities⁴ that affect actual open circuit potentials. Therefore, some of the chemical potential energy converts into heat. The electrical power generated by the fuel cell is the product of the current measured in amps and the operational voltage. Based on the application and economics, a typical operating fuel cell will have an operating voltage of between 0.55 volts and 0.80 volts. The ratio of the operating voltage and the theoretical maximum of 1.48 volts represents a simplified estimate of the stack electrical efficiency on a higher heating value (HHV⁵) basis.

As explained, resistance heat is also generated along with the power. Since the electric power is the product of the operating voltage and the current, the quantity of heat that must be removed from the fuel cell is the product of the current and the difference between the theoretical potential and the operating voltage. In most cases, the water produced by the fuel cell reactions exits the fuel cell as vapor, and therefore, the 1.23-volt LHV theoretical potential is used to estimate sensible heat generated by the fuel cell electrochemical process.

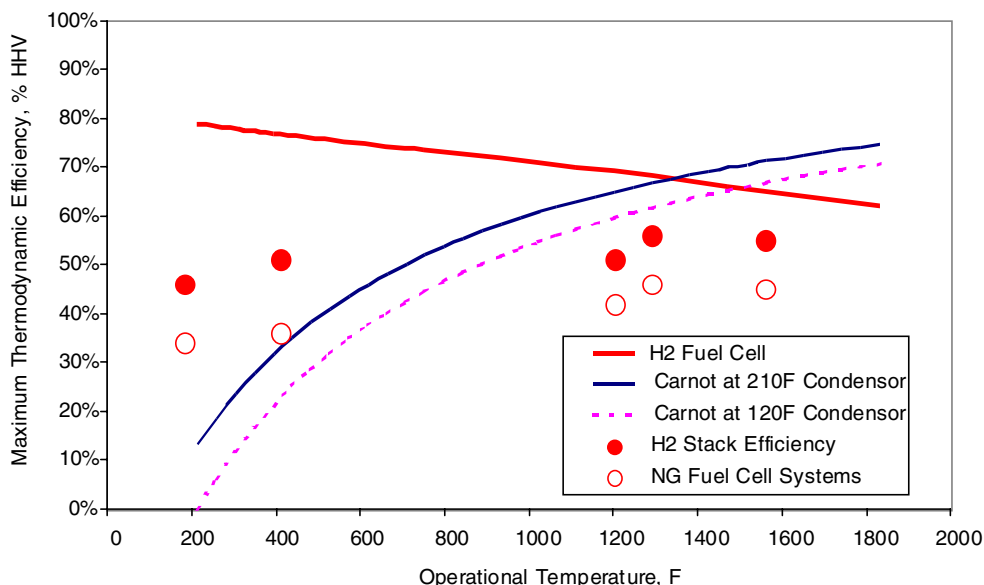
The overall electrical efficiency of the cell is the ratio of the power generated and the heating value of the hydrogen consumed. The maximum thermodynamic efficiency of a hydrogen fuel cell is the ratio of the Gibbs free energy and the heating value of the hydrogen. The Gibbs free energy decreases with increasing temperatures, because the product water produced at the elevated temperature of the fuel cell includes the sensible heat of that temperature, and this energy cannot be converted into electricity without the addition of a thermal energy conversion cycle (such as a steam turbine). Therefore, the maximum efficiency of a pure fuel cell system decreases with increasing temperature. **Figure 3** illustrates this characteristic in comparison to

⁴ Irreversibilities are changes in the potential energy of the chemical that are not reversible through the electrochemical process. Typically, some of the potential energy is converted into heat even at open circuit conditions when current is not flowing. A simple example is the resistance to ionic flow through the electrolyte while the fuel cell is operating. This potential energy “loss” is really a conversion to heat energy, which cannot be reconverted into chemical energy directly within the fuel cell.

⁵ Most of the efficiencies quoted in this report are based on higher heating value (HHV), which includes the heat of condensation of the water vapor in the products.

the Carnot cycle efficiency limits through a condenser at 50 and 100°C.⁶ This characteristic has led system developers to investigate hybrid fuel cell-turbine combined cycle systems to achieve system electrical efficiencies in excess of 70% HHV.

Figure 3. Effect of Operating Temperature on Fuel Cell Efficiency



Source: Siemens/Westinghouse Electric Corp.

Fuel Cell Stacks

Practical fuel cell systems require voltages higher than 0.55 to 0.80. Combining several cells in electrical series into a fuel cell stack achieves this. Typically, there are several hundred cells in a single cell stack. Increasing the active area of individual cells manages current flow. Typically, cell area can range from 100 cm² to over 1 m² depending on the type of fuel cell and application power requirements.

Fuel Processors

In distributed generation applications, the most viable fuel cell technologies use natural gas as the system's fuel source. To operate on natural gas or other fuels, fuel cells require a fuel processor or reformer, a device that converts the fuel into the hydrogen-rich gas stream. While adding fuel flexibility to the system, the reformer also adds significant cost and complexity. There are three primary types of reformers: steam reformers, autothermal reformers, and partial oxidation reformers. The fundamental differences are the source of oxygen used to combine with the carbon within the fuel to release the hydrogen gases and the thermal balance of the chemical process. Steam reformers use steam, while partial oxidation units use oxygen gas, and autothermal reformers use both steam and oxygen.

⁶ Larminie, James and Andrew Dicks, Fuel Cell Systems Explained. John Wiley & Sons, Ltd., West Sussex, England, 2000.

Steam reforming is extremely endothermic and requires a substantial amount of heat input. Autothermal reformers typically operate at or near the thermal neutral point, and therefore, do not generate or consume thermal energy. Partial oxidation units combust a portion of the fuel (i.e. partially oxidize it), releasing heat in the process. When integrated into a fuel cell system that allows the use of anode-off gas, a typical natural gas reformer can achieve conversion efficiencies in the 75 to 90% LHV range, with 83 to 85% being an expected level of performance. These efficiencies are defined as the LHV of hydrogen generated divided by the LHV of the natural gas consumed by the reformer.

Some fuel cells can function as *internally steam reforming* fuel cells. Since the reformer is an endothermic catalytic converter and the fuel cell is an exothermic catalytic oxidizer, the two combine into one with mutual thermal benefits. More complex than a pure hydrogen fuel cell, these types of fuel cells are more difficult to design and operate. While combining two catalytic processes is difficult to arrange and control, these internally reforming fuel cells are expected to account for a significant market share as fuel cell based DG becomes more common.

Power Conditioning Subsystem

The fuel cell generates direct current electricity, which requires conditioning before serving a DG application. Depending on the cell area and number of cells, this direct current electricity is approximately 200 to 400 volts per stack. If the system is large enough, stacks can operate in series to double or triple individual stack voltages. Since the voltage of each individual cell decreases with increasing load or power, the output is considered an unregulated voltage source. The power conditioning subsystem boosts the output voltage to provide a regulated higher voltage input source to an electronic inverter. The inverter then uses a pulse width modulation technique at high frequencies to generate simulated alternating current output. The inverter controls the frequency of the output, which can be adjusted to enhance power factor characteristics. Because the inverter generates alternating current within itself, the output power is generally clean and reliable. This characteristic is important to sensitive electronic equipment in premium power applications. The efficiency of the power conditioning process is typically 92 to 96%, and is dependent on system capacity and input voltage-current characteristic.

Types of Fuel Cells

There are five basic types of fuel cell under consideration for DG applications. The fuel cell's electrolyte or ion conduction material defines the basic type. Two of these fuel cell types, polymer electrolyte membrane (PEM) and phosphoric acid fuel cell (PAFC), have acidic electrolytes and rely on the transport of H^+ ions. Two others, alkaline fuel cell (AFC) and carbonate fuel cell (MCFC), have basic electrolytes that rely on the transport of OH^- and CO_3^{2-} ions, respectively. The fifth type, solid oxide fuel cell (SOFC), is based on a solid-state ceramic electrolyte in which oxygen ions (O^{2-}) are the conductive transport ion.

Each fuel cell type operates at optimum temperature, which is a balance between the ionic conductivity and component stability. These temperatures differ significantly among the five basic types, ranging from near ambient to as high as 1800°F. The proton conducting fuel cell

type generates water at the cathode and the anion conducting fuel cell type generates water at the anode. **Table 1** below presents fundamental characteristics for each fuel cell type.

Table 1. Characteristics of Major Fuel Cell Types

| | PEMFC | AFC | PAFC | MCFC | SOFC |
|--|---|---|--|--|---|
| Type of Electrolyte | H ⁺ ions (with anions bound in polymer membrane) | OH ⁻ ions (typically aqueous KOH solution) | H ⁺ ions (H ₃ PO ₄ solutions) | CO ₃ ²⁻ ions (typically, molten LiKaCO ₃ eutectics) | O ²⁻ ions (Stabilized ceramic matrix with free oxide ions) |
| Typical construction | Plastic, metal, or carbon | Plastic, metal | Carbon, porous ceramics | High temp metals, porous ceramic | Ceramic, high temp metals |
| Internal reforming | No | No | No | Yes, Good Temp Match | Yes, Good Temp Match |
| Oxidant | Air to O ₂ | Purified Air to O ₂ | Air to Enriched Air | Air | Air |
| Operational Temperature | 150- 180°F (65-85°C) | 190-500°F (90-260°C) | 370-410°F (190-210°C) | 1,200-1,300°F (650-700°C) | 1,350-1,850°F (750-1,000°C) |
| DG System Level Efficiency, % HHV | 25 to 35% | 32 to 40% | 35 to 45% | 40 to 50% | 45 to 55% |
| Primary Contaminate Sensitivities | CO, Sulfur, and NH ₃ | CO, CO ₂ , and Sulfur | CO < 1%, Sulfur | Sulfur | Sulfur |

Source: Energy Nexus Group

PEMFC (Proton Exchange Membrane Fuel Cell or Polymer Electrolyte Membrane)

NASA developed this type of fuel cell in the 1960s for the first manned spacecraft. The PEMFC uses a solid polymer electrolyte and operates at low temperatures (about 200°F). Over the past ten years, the PEMFC has received significant media coverage due to the large auto industry investment in the technology. Due to their modularity and potential for simple manufacturing, reformer/PEMFC systems for residential DG applications have attracted considerable development capital. PEMFC's have high power density and can vary their output quickly to meet demand. This type of fuel cell is highly sensitive to CO poisoning.

AFC (Alkaline Fuel Cell)

F.T. Bacon in Cambridge, England first demonstrated AFC as a viable power unit during the 1940s and 1950s. NASA later developed and used this fuel cell on the Apollo spacecraft and on the space shuttles. AFC technology uses alkaline potassium hydroxide as the electrolyte. The primary advantages of AFC technology are improved performance (electrical efficiencies above 60% HHV), use of non-precious metal electrodes, and the fact that no unusual materials are needed. The primary disadvantage is the tendency to absorb carbon dioxide, converting the alkaline electrolyte to an aqueous carbonate electrolyte that is less conductive. The attractiveness of AFC has declined substantially with the interest and improvements in PEMFC technology.

PAFC (Phosphoric Acid Fuel Cell)

PAFC uses phosphoric acid as the electrolyte and is generally considered the most established fuel cell technology. The first PAFC DG system was designed and demonstrated in the early 1970s. PAFCs are capable of fuel-to-electricity efficiencies of 36% HHV or greater. A 200 kW PAFC has been commercially available since the early 1990s. Over 200 of these commercial units were manufactured, delivered, and are operating in the U.S., Europe, and Japan. The current 200 kW product is reported to have a stack lifetime of over 40,000 hours, units with nearly eight years of operation, and commercially based reliabilities in the 90 to 95% range. The major market barrier has been the initial installed cost that has not yet fallen below the \$4,500 to \$5,500/kW range.

MCFC (Molten Carbonate Fuel Cell)

The MCFC uses an alkali metal carbonate (Li, Na, K) as the electrolyte and has a developmental history that dates back to the early part of the twentieth century. Due to its operating temperature range of 1,100 to 1,400°F, the MCFC holds promise in both CHP and DG applications. This type of fuel cell can be internally reformed, can operate at high efficiencies (50% HHV), and is relatively tolerant of fuel impurities. Government/industry R&D programs during the 1980s and 1990s resulted in several individual pre-prototype system demonstrations. FuelCell Energy is presently the only company with a commercial molten carbonate fuel cell. The primary technical issue with MCFC technologies is the degradation of cell components due to the corrosive nature of the electrolyte/operating temperature combination.

SOFC (Solid Oxide Fuel Cell)

The SOFC uses solid, nonporous metals oxide electrolytes and is generally considered less mature in its development than the MCFC and PAFC technologies. Several SOFC units up to 100 kW in size and based on a concentric tubular design have been built and tested.⁷ In addition, there are many companies developing planar SOFC designs, which offer higher power densities and lower costs than the tubular design, but these have yet to achieve the reliability of the tubular design. Despite relative immaturity, the SOFC has several advantages (high efficiency, stability and reliability, and high internal temperatures) that have attracted development support. The SOFC has projected service electric efficiencies of 45 to 60% and higher, for larger hybrid, combined cycle plants. Efficiencies for smaller SOFC DG units are expected to be in the 50% range.

Stability and reliability of the SOFC are due to an all-solid-state ceramic construction. Test units have operated in excess of 10 years with acceptable performance. The high internal temperatures of the SOFC are both an asset and a liability. As an asset, high temperatures make internal reforming possible. As a liability, these high temperatures add to materials and mechanical design difficulties, which reduces stack life and increases cost. While SOFC research has been ongoing for 30 years, costs of these stacks are still comparatively high.

Design Characteristics

The features that have the potential to make fuel cell systems a leading prime mover for CHP and other distributed generation applications include:

⁷ By Siemens/Westinghouse Electric Corp.

| | |
|-----------------------|--|
| Size range: | Fuel cell systems are constructed from individual cells that generate 100 W to 2 kW per cell. This allows systems to have extreme flexibility in capacity. Systems under development for DG application range in sizes from 5 kW to 2 MW. Multiple systems can operate in parallel at a single site to provide incremental capacity. |
| Thermal output: | Fuel cells can achieve overall efficiencies in the 65 to 85% range. Waste heat can be used primarily for domestic hot water applications and space heating. |
| Availability: | The commercially available 200 kW PC25 system fleet (200-plus units) has demonstrated greater than 90% availability during over four million operating hours. As fuel cell systems mature, their reliability should improve. |
| Part-load operation: | Fuel cell stack efficiency improves at lower loads, which results in a system electric efficiency that is relatively steady down to one-third to one-quarter of rated capacity. This provides systems with excellent load following characteristics. |
| Cycling: | While part-load efficiencies of fuel cells are generally high, MCFC and SOFC fuel cells require long heat-up and cool-down periods, restricting their ability to operate in many cyclic applications. |
| High quality power: | Electrical output is computer grade power, meeting critical power requirements without interruption. This minimizes lost productivity, lost revenues, product loss, or opportunity cost. |
| Reliability and life: | Since only auxiliary components have moving parts, the reliability of fuel cells is expected to be high. A few of the initial PC25 systems have achieved operational lives of 70,000 hours. |
| Emissions: | The only combustion within a fuel cell system is the low energy content hydrogen stream exhausted from the stack. This stream is combusted within the reformer and can achieve emissions signatures of < 2 ppmv CO, <1 ppmv NO _x and negligible SO _x (on 15% O ₂ , dry basis). |
| Efficiency: | Different types of fuel cells have varied efficiencies. Depending on the type and design of fuel cells, electric efficiency ranges from 30% to over 50% HHV. |
| Quiet Operation: | Conversational level (60dBA @ 30 ft.), acceptable for indoor installation. |

| | |
|------------------|---|
| Siting and Size: | Indoor or outdoor installation. |
| Fuel Use: | The primary fuel source for the fuel cell is hydrogen, which can be obtained from natural gas, coal gas, methanol, and other fuels containing hydrocarbons. |

Performance Characteristics

Fuel cell performance is a function of the type of fuel cell and its capacity. Since the fuel cell system is a series of chemical, electrochemical, and electronic subsystems, the optimization of electric efficiency and performance characteristics can be a challenging engineering task. The electric efficiency calculation example provided in the next section illustrates this.

Table 2 summarizes performance characteristics for representative commercially available and developmental natural gas fuel cell CHP systems over the 10 kW to 2 MW size range. This size range covers the majority of the market applications currently envisioned for fuel cell CHP and represents the most likely units to be commercially introduced within the next five years. Of the systems included in **Table 2**, the only commercially available at this time is the PAFC product, first introduced in 1992. The other systems are in various phases of prototype demonstration. Cost and performance estimates for these systems are based on initial market entry targets. The capital cost estimate for the PAFC system represents published cost from the manufacturer for lots of three or more units. Since the other systems are just emerging from their demonstration phases, pricing and costing information are subjective and estimates should be considered within the plus or minus thirty percent range.

Table 2. Fuel Cell CHP - Typical Performance Parameters

| Cost and Performance Characteristics⁸ | System 1 | System 2 | System 3 | System 4 | System 5 | System 6 |
|---|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Fuel Cell Type | PAFC | PEM | PEM | MCFC | MCFC | SOFC |
| Nominal Electricity Capacity (kW) | 200 | 10 | 200 | 250 | 2,000 | 100 |
| Commercial Status 2002 ⁹ | Com'l | Demo | Demo | Demo | Demo | Demo |
| Operating Temperature (°F) | 400 | 150 | 150 | 1200 | 1200 | 1750 |
| Package Cost (2002 \$/kW) ¹⁰ | 3,850 | 4,700 | 2,950 | 4,350 | 2,400 | 2,850 |
| Total Installed Cost (2002 \$/kW) ¹¹ | 4,500 | 5,500 | 3,600 | 5,000 | 2,800 | 3,500 |
| O&M Costs (\$/kW) ¹² | 0.029 | 0.033 | 0.023 | 0.043 | 0.033 | 0.023 |
| Electric Heat Rate (Btu/kWh) ¹³ | 9,480 | 11,370 | 9,750 | 7,930 | 7,420 | 7,580 |
| Electrical Efficiency (% HHV) ¹⁴ | 36% | 30% | 35% | 43% | 46% | 45% |
| Fuel Input (MMBtu/hr) | 1.90 | 0.10 | 2.00 | 2.00 | 14.80 | 0.80 |
| CHP Characteristics | | | | | | |
| Heat Avail. >160°F (MMBtu/hr) | 0.37 | 0.00 | 0.00 | 0.22 | 1.89 | 0.10 |
| Heat Avail. <160°F (MMBtu/hr) | 0.37 | 0.04 | 0.72 | 0.22 | 1.67 | 0.09 |
| Heat Output (MMBtu/hr) | 0.74 | 0.04 | 0.72 | 0.44 | 3.56 | 0.19 |
| Heat Output (kW equivalent) | 217 | 13 | 211 | 128 | 1043 | 56 |
| Total CHP Efficiency (%), HHV ¹⁵ | 75% | 68% | 72% | 65% | 70% | 70% |
| Power/Heat Ratio ¹⁶ | 0.92 | 0.77 | 0.95 | 1.95 | 1.92 | 1.79 |
| Net Heat Rate (Btu/kWh) ¹⁷ | 4,860 | 6,370 | 5,250 | 5,730 | 5,200 | 5,210 |
| Effective Electrical Eff (%), HHV | 70.3% | 53.6% | 65.0% | 59.5% | 65.7% | 65.6% |

Source: Energy Nexus Group.

⁸ Data are representative typical values for developmental systems based on available information from fuel cell system developers. Only the PAFC data are representative of a commercial product available in 2002. Developers include but are not limited to UTC Fuel Cells, Toshiba, Ballard Power, Plug Power, Fuel Cell Energy, Siemens-Westinghouse, H-Power, Hydrogenics, Honeywell, Fuji, IHI, Global Thermal, Mitsubishi Heavy Industries, and Ztek.

⁹ Com'l = Commercially Available; Demo = Multiple non-commercial demonstrations completed or underway in field sites with potential customers; Lab = Characteristics observed in laboratory validation testing of complete systems; Exp = Only experimental prototypes have been tested.

¹⁰ Packaged Cost includes estimates of typical costs for a CHP compatible system with grid interconnection functionality built into power conditioning subsystem.

¹¹ Total Installed Cost include estimates for packaged cost plus electrical isolation equipment, hot water CHP interconnections, site labor and preparation, construction management, engineering, contingency, and interest during construction. See Table 3.

¹² O&M costs are estimated based on service contract nominal rate, consumables, fixed costs, and sinking fund for stack replacement at end of life. See Table 4.

¹³ All equipment manufacturers quote heat rates in terms of the lower heating value (LHV) of the fuel. On the other hand, the usable energy content of fuels is typically measured on a higher heating value (HHV) basis. In addition, electric utilities measure power plant heat rates in terms of HHV. For natural gas, the average heat content of natural gas is 1,030 Btu/scf on an HHV basis and 930 Btu/scf on an LHV basis – or about a 10% difference.

¹⁴ Electrical efficiencies are net of parasitic and conversion losses.

¹⁵ Total Efficiency = (net electric generated + net heat produced for thermal needs)/total system fuel input

¹⁶ Power/Heat Ratio = CHP electrical power output (Btu)/ useful heat output (Btu)

¹⁷ Effective Electrical Efficiency = (CHP electric power output)/(Total fuel into CHP system – total heat recovered/0.8). Equivalent to 3,412 Btu/kWh/Net Heat Rate and Net Heat Rate = 3412/Effective Elec Eff.

Heat rates and efficiencies shown were taken from manufacturers' specifications, industry publications, or are based on the best available data for developing technologies. Available thermal energy was calculated from estimated overall efficiency for these systems. CHP thermal recovery estimates are based on producing low quality heat for domestic hot water process or space heating needs. This feature is generally acceptable for commercial/institutional applications where it is more common to have hot water thermal loads.

The data in the table show that electrical efficiency increases as the operating temperature and size of the fuel cell increases. As electrical efficiency increases, the absolute quantity of thermal energy available to produce useful thermal energy decreases per unit of power output, and the ratio of power to heat for the CHP system generally increases. A changing ratio of power to heat impacts project economics and may affect the decisions that customers make in terms of CHP acceptance, sizing, and the desirability of selling power.

Electrical Efficiency

As with all generation technologies, the electrical efficiency is the ratio of the power generated and the heating value of the fuel consumed. Because the fuel cell system has several subsystems in series, the electrical efficiency of the DG unit is the multiple of the efficiencies of the individual section. The concept of stack electric efficiency was introduced earlier. The following calculates the electric efficiency of a fuel cell system:

$$\text{ElecEff} = (\text{FPS Eff} * \text{H}_2 \text{ Utilization} * \text{Stack Eff} * \text{PC Eff}) * (\text{HHV/LHV ratio of the fuel})$$

| | |
|----------------------------|--|
| Where: FPS Eff | = Fuel Processing Subsystem Efficiency, LLV |
| | = (LHV of H ₂ Generated/LHV of Fuel Consumed) |
| H ₂ Utilization | = % of H ₂ actually consumed in the stack |
| Stack Eff | = (Operating Voltage/Energy Potential ~1.23 volts) |
| PC Eff | = AC power delivered/(DC power generated) |
| | (auxiliary loads are assumed DC loads here) |

$$\begin{aligned} \text{For example: PAFC} &= (84\% \text{FPS}) * (83\% \text{ util}) * (0.75\text{V}/1.25\text{V}) * (95\% \text{PC}) * (0.9 \text{HHV/LHV}) \\ &= 36\% \text{ electric efficiency HHV} \end{aligned}$$

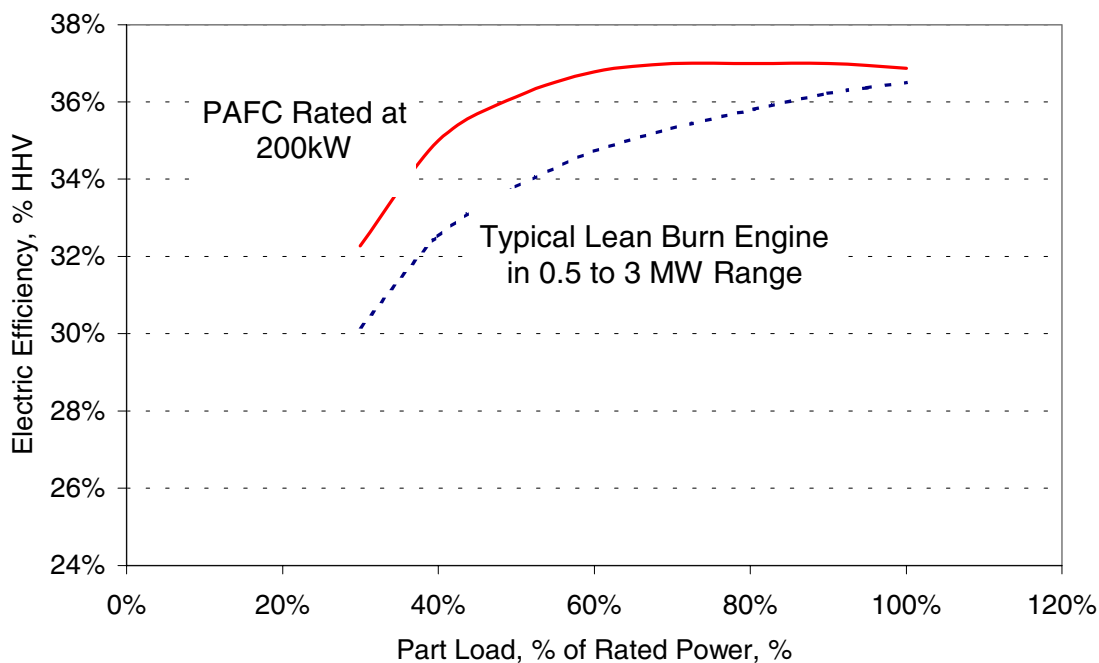
As the operating temperature range of the fuel cell system increases, the electric efficiency of the systems tends to increase. Although the maximum thermodynamic efficiency decreases as shown in **Figure 2**, improvements in reformer subsystem integration and increases in reactant activity balance out to provide the system level increase. Advanced high temperature MCFC and SOFC systems are projected to achieve simple cycle efficiencies in the range of 50 to 55% HHV, while hybrid combined fuel cell-heat engine systems are calculated to achieve efficiencies above 60% in DG applications.

Part-Load Performance

In power generation and CHP applications, fuel cell systems follow either the electric or thermal load of the applications to maximize DG energy economics. **Figure 4** shows the part-load efficiency curve for a market entry PAFC fuel cell in comparison to a typical lean burn natural

gas engine. The efficiency at 50% load is within 2% of its full load efficiency characteristic. As the load decreases further, the curve becomes somewhat steeper, as inefficiencies in air blowers and the fuel processor begin to override the stack efficiency improvement.

Figure 4. Comparison of Part Load Efficiency Derate



Source: Gas Research Institute, Caterpillar, and Energy Nexus Group.

Effects of Ambient Conditions on Performance

Fuel cells are rated at ISO conditions of 77°F and 0.987 atmospheres (1 bar) pressure. Fuel cell system performance – both output and efficiency – can degrade as ambient temperature or site elevation increases. Ancillary equipment performance, primarily the air handling blowers or compressors, accounts for the degradation of performance. Performance degradations will be greater for pressurized systems operating with turbo-chargers or small air compressors as their primary air supply components.

Heat Recovery

The economics of fuel cells in on-site power generation applications depend less on effective use of the thermal energy recovered than is the case with lower efficiency prime movers, but thermal load displacements improves operating economics as in any CHP application. Generally, the stack and reformer subsystems contain 25% of the inlet fuel energy in the form of higher quality thermal energy. The exhaust gases (includes the latent heat of the product water generated in the fuel cell) contain another 25% of the recoverable energy. The most common use of this heat is to generate hot water or low-pressure steam for process use or for space heating, process needs, or domestic hot water.

Heat can generally be recovered in the form of hot water or low-pressure steam (< 30 psig), but the quality of heat is dependent on the type of fuel cell and its operating temperature. The one exception to this is the PEM fuel cell, which operates at temperatures below 100°C, and therefore has only low quality heat.

As an example, there are four primary potential sources of usable waste heat from a fuel cell system: exhaust gas including water condensation, stack cooling, anode-off gas combustion, and reformer heat. The PAFC system achieves 36% electric efficiency and 72% overall CHP efficiency, which means that it has a 36% thermal efficiency or power to heat ratio of one. Of the available heat, 25 to 45% is recovered from the stack-cooling loop that operates at approximately 400°F and can deliver low- to medium-pressure steam. The exhaust gas-cooling loop provides the balance of the heat and serves two functions. The first is condensation of product water, thus rendering the system water self-sufficient, and the second is the recovery of by-product heat. Since its primary function is water recovery, the balance of the heat available from the PAFC fuel cell is recoverable with 120°F return and 300°F supply temperatures. This tends to limit the application of this heat to domestic hot water applications. Maximum system efficiency occurs when all of the available anode-off gas heat and internal reformer heat is used internally.

In the case of SOFC and MCFC fuel cells, medium-pressure steam (up to about 150 psig) can be generated from the fuel cell's high temperature exhaust gas, but the primary use of these hot exhaust gas is in recuperative heat exchange with the inlet process gases. Like engine and turbine systems, the fuel cell exhaust gas can be used directly for process drying.

Performance and Efficiency Enhancements

Air is fed to the cathode side of the fuel cell stack to provide the oxygen needed for the power generation process. Typically, 50 to 100% more air passes through the cathode than the fuel cell reactions require. The fuel cell operated at near-ambient pressure, or at elevated pressures to enhance stack performance. Increasing the pressure, and therefore the partial pressure of the reactants, increases stack performance by reducing the electrode over potentials associated with moving the reactants into the electrodes where the catalytic reaction occurs. It also improves the performance of the catalyst. Assuming optimistic compressor characteristics, these improvements appear to optimize at approximately three atmospheres pressure.¹⁸ More realistic assumptions often result in optimizations at ambient pressure where air movement requires the least energy. Because of these characteristics, developers focus on both pressurized and ambient pressure systems.

Capital Cost

This section provides estimates for the installed cost of fuel cell systems designed for DG applications. Only CHP configurations are presented because the majority of developments appear to integrate heat recovery capability primarily to support product water condensation and self-sufficiency. Capital costs (equipment and installation) are estimated in **Table 3** for the six typical fuel cell systems presented in **Table 1** in the 10 kW to 2 MW size range. Estimates are

¹⁸ Ibid., p. 90.

“typical” budgetary price levels. Installed costs can vary significantly depending on the scope of the plant equipment, geographical area, competitive market conditions, special site requirements, prevailing labor rates, and whether the system is a new or retrofit application.

Based on commercially available information and internal analysis, each of five major component groups with approximately twenty major components was used to define the individual fuel cell systems and to develop total package cost estimates. Cost and pricing information was estimated in constant 2002 dollars and totaled across major component groups to achieve the estimated packaged cost of each system. This process allowed for uniform estimates for similar components of similar capacity such as the power electronics, and adjustments for components such as the cell stack and reformer subsystems due to the technology differences and product requirements

Following the above approach, each fuel cell system was broken down into the following five major component groups or subsystems:

- Stack subsystem – consisting of the fuel cell stacks, feed gas manifolds, and power take-offs.
- Fuel processing subsystem – consisting of fuel management controls, reformer, steam generators, shift reactors, sulfur absorbent beds, and ancillary components.
- Power and electronic subsystem – consisting of a solid-state boost regulator, DC to AC inverters, grid interconnect switching, load management and distribution hardware, and inverter controller and overall supervisory controller.
- Thermal management subsystem – consisting of the stack cooling system, heat recovery and condensing heat exchangers.
- Ancillary subsystems – consisting of the process air supply blowers, water treatment system, safety controls and monitoring, cabinet ventilation fans, and other miscellaneous components.

From a cost and complexity standpoint, each individual system and system developer has a different perspective on the details of these subsystems. The stack subsystem represents from 25 to 40% of equipment cost, the fuel processing subsystem from 25 to 30%, the power and electronics subsystem from 10 to 20%, the thermal management subsystem from 10 to 20%, and ancillary subsystems from 5 to 15%. One of the major issues with fuel cell systems is process complexities and the cost of equipment to maintain expanded features and characteristics.

The cost of the basic fuel cell package plus the costs for added systems needed for the particular application comprise the total equipment cost. The total plant cost consists of total equipment cost plus installation labor and materials (including site work), engineering, project management (including licensing, insurance, commissioning and startup), and financial carrying costs during construction. The installation costs of fuel cell systems are relatively consistent with engine-based equipment. The range of \$400 to \$800/kW used in **Table 2** reflects this similarity but include slight increases due to issues that will arise because of the uniqueness of the equipment. No additional costs were applied for emission controls technologies or permitting delays.

Table 3. Estimated Capital Cost for Typical Fuel Cell Systems in Grid Interconnected CHP Applications (\$/kW)*

| Installed Cost Components | System 1 | System 2 | System 3 | System 4 | System 5 | System 6 |
|---|----------|----------|----------|----------|----------|----------|
| Nominal Capacity (kW) | 200 | 10 | 200 | 250 | 2000 | 100 |
| Fuel Cell Type | PAFC | PEM | PEM | MCFC | MCFC | SOFC |
| Equipment Costs (2002 \$/kW) | | | | | | |
| Packaged Cost | 3,850 | 4,700 | 2,950 | 4,350 | 2,400 | 2,850 |
| Grid Isolation Breakers ¹⁹ | 100 | 250 | 100 | 100 | 15 | 120 |
| Materials and Labor ²⁰ | 272 | 100 | 272 | 280 | 230 | 250 |
| Total Process Capital | 4,222 | 5,050 | 3,370 | 4,780 | 2,645 | 2,270 |
| Other Site Costs (2002 \$/kW) ²¹ | | | | | | |
| Proj. & Const. Management | 124 | 280 | 124 | 112 | 80 | 168 |
| Engineering and Fees | 52 | 90 | 52 | 60 | 25 | 72 |
| Contingencies | 94 | 80 | 94 | 90 | 20 | 30 |
| Interest during Construction | 8 | 0 | 8 | 8 | 30 | 10 |
| | | | | | | |
| Total Installed Cost (2002 \$/kW) | 4,500 | 5,500 | 3,600 | 5,000 | 2,800 | 3,500 |

* Estimated capital costs for current technology fuel cell systems in the 2003/04 timeframe.

Source: Energy Nexus Group.

Maintenance

Maintenance costs for fuel cell systems vary with type of fuel cell, size, and maturity of the equipment. Some of the typical costs that need to be included are:

- Maintenance labor.
- Ancillary replacement parts and material such as air and fuel filters, reformer igniter or spark plug, water treatment beds, flange gaskets, valves, electronic components, etc., and consumables such as sulfur adsorbent bed catalysts and nitrogen for shutdown purging.
- Major overhauls include shift catalyst replacement (3 to 5 years), reformer catalyst replacement (5 years), and stack replacement (4 to 8 years).

In-house personnel can perform basic maintenance, or it can be contracted out to manufacturers, distributors, or dealers under service contracts. Details of full maintenance contracts (covering all recommended service) and costing are not generally available, but are estimated at 0.7 to 2.0 cents/kWh excluding the stack replacement cost sinking fund. Maintenance for initial

¹⁹ Only grid isolation breakers included because functionality of grid interconnection and isolation has been included into the power conditioning subsystem with package cost. For example, \$100/kW was included for System 1 and System 3 at 200 kW capacity.

²⁰ Materials and labor estimates were based on typical engine CHP systems for units between 100 and 2,000 kW. The 10 kW system was estimated based on appliance type residential installations.

²¹ Other site-related costs were estimated based on the extrapolated data from typical engine CHP systems for units between 100 and 2,000 kW. The interest during construction for the 10 kW system was set at zero because of the residential appliance-like nature of equipment.

commercial fuel cells has included remote monitoring of system performance and conditions and an allowance for predictive maintenance. Routine short interval inspections/adjustments and periodic replacement of filters (projected at intervals of 2,000 to 4,000 hours) comprise the recommended service.

Table 4 presents maintenance costs based on service contracts consisting of routine inspections and scheduled overhauls of the fuel cell system and are prorated based on comparable engine generator service contracts. Stack life and replacement costs are based on developers' estimates for initial units. Overall, maintenance costs are based on 8,000 annual operating hours expressed in terms of annual electricity generation.

**Table 4. Estimated Operating and Maintenance Costs
Of Typical CHP Fuel Cell Systems***

| O&M Cost Analysis (2002 \$) ²² | System 1 | System 2 | System 3 | System 4 | System 5 | System 6 |
|---|----------|----------|----------|----------|----------|----------|
| Nominal Capacity (kW) | 200 | 10 | 200 | 250 | 2,000 | 100 |
| Fuel Cell Type | PAFC | PEM | PEM | MCFC | MCFC | SOFC |
| | | | | | | |
| Variable Service Contract (\$/kWh) | 0.0087 | 0.0121 | 0.0087 | 0.0072 | 0.0054 | 0.0102 |
| Variable Consumables (\$/kWh) | 0.0002 | 0.0002 | 0.0002 | 0.0002 | 0.0002 | 0.0002 |
| Fixed (\$/kW-yr) | 6.5 | 18.0 | 6.5 | 5.0 | 2.1 | 10.0 |
| Fixed(\$/kWh @ 8,000 hrs/yr) | 0.0008 | 0.0023 | 0.0008 | 0.0006 | 0.0003 | 0.0013 |
| Stack Fund (\$/kWh) ²³ | 0.0193 | 0.0188 | 0.0132 | 0.0350 | 0.0275 | 0.0125 |
| Stack Life (yrs) | 5 | 4 | 4 | 4 | 4 | 8 |
| Recovery Factor (%) | 30% | 50% | 35% | 30% | 20% | 20% |
| | | | | | | |
| Net O&M cost (\$/kWh) | 0.029 | 0.033 | 0.023 | 0.043 | 0.033 | 0.023 |

* Estimated costs for current technology fuel cell systems in the 2003/04 timeframe
Source: Energy Nexus Group.

Fuels

Fuel cell systems operate on a variety of alternative gaseous fuels since the primary fuel source is hydrogen produced from hydrocarbon fuels. These including the following:

²² Maintenance costs presented in **Table 4** are based on 8,000 operating hours expressed in terms of annual electricity generation. Fixed costs are based on an interpolation of engine manufacturers' estimates and applied to fuel cell system. The variable component of the O&M cost represents the inspections and minor procedures that are normally conducted by the original equipment manufacturer through a service agreement, and have been estimated based on 60% of reciprocating engine service contracts. Major overhaul procedures primarily representing stack replacements have been handled as a separate item.

²³ Stack replacement costs have been estimated = (stack original cost*(1-recovery factor))/(stack life*8000hrs/yr). Stack life was estimated based on type of fuel cell. Recovery factor was based on catalyst recovery, metal scrap value and non-repeat hardware value at end of life. All estimates are considered first cut projections and have an uncertainty of +/- one year and +/- 15%. The small PEM recovery factor was increased due to its higher non-repeat component cost.

- Liquefied petroleum gas (LPG) – propane and butane mixtures.
- Sour gas - unprocessed natural gas as it comes directly from the gas well.
- Biogas – any of the combustible gases produced from biological degradation of organic wastes, such as landfill gas, sewage digester gas, and animal waste digester gas.
- Industrial waste gases – flare gases and process off-gases from refineries, chemical plants and steel mill.
- Manufactured gases – typically low- and medium-Btu gas produced as products of gasification or pyrolysis processes.

Factors that impact the operation of a fuel cell system with alternative gaseous fuels include:

- Volumetric heating value – Since the fuel cell's fuel processing system initially reforms the fuel, the lower energy content fuels simply result in a less concentrated hydrogen-rich gas stream feeding the anode. This will cause some loss in stack performance, which can affect the stack efficiency, stack capacity, or both. Increased pressure drops through various flow passages can also decrease the fine balance developed in fully integrated systems.
- Contaminants are the major concern when operating on alternative gaseous fuels. If any additional sulfur and other components (e.g., chlorides) can be removed prior to entering the fuel processing catalyst, there should be no performance or life impact. If not, the compounds can cause decreased fuel processor catalyst life and potentially impact stack life.

Availability

Although fuel cell systems are perceived as low maintenance devices, their technical immaturity and market entry status cause concern in DG applications. Close attention has been given to the availability of the initial fleet of over 200 commercial PAFC fuel cell units. In a recent 12-month period, the fleet of units in North America achieved 89% availability, with 94% during the last 30 days of the period. In premium power applications, 100% customer power availability, and 96.3% fleet availability has been reported during the same period.²⁴ This performance is a preliminary indicator that fuel cells can provide high levels of availability, even in high-load factor applications.

The use of multiple units at a site can further increase the availability of the overall facility. Analysis conducted during the fuel cell field demonstration programs of the 1980s indicated that three to five units sized to 120% of application load, operating in parallel, could provide 99.99%-plus availability under typical commercial building load profile characteristics.

²⁴ According to manufacturer United Technology Corporation (www.UTCFuelCells.com, 3/28/02).

Emissions

Fuel cell systems produce few emissions since the primary power generation process does not involve combustion. In fact, the fuel processing subsystem is the only significant source of emissions. The anode-off gas that typically consists of 8 to 15% hydrogen is combusted in a catalytic or surface burner element to provide heat to the reforming process. The temperature of this lean combustion can be maintained at less than 1,800°F, which also prevents the formation of oxides of nitrogen (NO_x) but is sufficiently high to ensure oxidation of carbon monoxide (CO) and volatile organic compounds (VOCs – unburned, non-methane hydrocarbons). Typically, an absorbed bed before the fuel processor removes and eliminates other pollutants such as oxides of sulfur (SO_x).

Nitrogen Oxides (NO_x)

Three mechanisms form NO_x : thermal NO_x , prompt NO_x , and fuel-bound NO_x . Thermal NO_x is the fixation of atmospheric oxygen and nitrogen, which occurs at high combustion temperatures. Flame temperature and residence time are the primary variables that affect thermal NO_x levels. The rate of thermal NO_x formation increases rapidly with flame temperature. Early reactions of nitrogen molecules in the combustion air and hydrocarbon radicals from the fuel form prompt NO_x . It forms within the flame and typically is on the order of 1 ppm at 15% O_2 , and is usually much smaller than the thermal NO_x formation. Fuel-bound NO_x forms when the fuel contains nitrogen as part of the hydrocarbon structure. Natural gas has negligible chemically bound fuel nitrogen. Fuel-bound NO_x can be at significant levels with liquid fuels.

Carbon Monoxide (CO)

CO and VOCs both result from incomplete combustion. CO emissions result when there is inadequate oxygen or insufficient residence time at high temperature. Cooling at the combustion chamber walls and reaction quenching in the exhaust process also contribute to incomplete combustion and increased CO emissions. Excessively lean conditions can lead to incomplete and unstable combustion and high CO levels.

Unburned Hydrocarbons

Volatile hydrocarbons, also called volatile organic compounds (VOCs), can encompass a wide range of compounds, some of which are hazardous air pollutants. When some portion of the fuel remains unburned or just partially burned these compounds discharge into the atmosphere. Some organics are carried over as unreacted trace constituents of the fuel, while others may be pyrolysis products of the heavier hydrocarbons in the gas. Volatile hydrocarbon emissions from reciprocating engines are normally reported as non-methane hydrocarbons (NMHCs). Methane is not a significant precursor to ozone creation and smog formation and is not currently regulated. Methane is a green house gas and may come under future regulations.

Carbon Dioxide (CO_2)

While not considered a pollutant in the ordinary sense of directly affecting health, emissions of carbon dioxide (CO_2) are of concern due to its contribution to global warming. Atmospheric warming occurs since solar radiation readily penetrates to the surface of the planet but infrared (thermal) radiation from the surface is absorbed by the CO_2 (and other polyatomic gases such as methane, unburned hydrocarbons, refrigerants, and volatile chemicals) in the atmosphere, with

resultant increase in temperature of the atmosphere. The amount of CO₂ emitted is a function of both fuel carbon content and system efficiency. The fuel carbon content of natural gas is 34 lbs carbon/MMBtu; oil is 48 lbs carbon/MMBtu; and (ash-free) coal is 66 lbs carbon/MMBtu.

Fuel Cell Emissions Characteristics

Table 6 illustrates the emission characteristics of fuel cell system. Fuel cell systems do not require any emissions control devices to meet current and projected regulations.

Table 6. Estimated Fuel Cell Emission Characteristics without Additional Controls*

| Emissions Analysis²⁵ | System 1 | System 2 | System 3 | System 4 | System 5 | System 6 |
|--|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Electricity Capacity (kW) | 200 | 10 | 200 | 250 | 2000 | 100 |
| Electrical Efficiency (HHV) | 36% | 30% | 35% | 43% | 46% | 45% |
| Fuel Cell Type | PAFC | PEM | PEM | MCFC | MCFC | SOFC |
| | | | | | | |
| Emissions²⁶ | | | | | | |
| NO _x (ppmv @ 15% O ₂) | 1.0 | 1.8 | 1.8 | 2.0 | 2.0 | 2.0 |
| NO _x (lb/MWh) | 0.03 | 0.06 | 0.06 | 0.06 | 0.05 | 0.05 |
| CO (ppmv @ 15% O ₂) | 2.0 | 2.8 | 2.8 | 2.0 | 2.0 | 2.0 |
| CO (lb/MWh) | 0.05 | 0.07 | 0.07 | 0.04 | 0.04 | 0.04 |
| VOC (ppmv @ 15% O ₂) | 0.7 | 0.4 | 0.4 | 0.5 | 1.0 | 1.0 |
| VOC (lb/MWh) | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| CO ₂ (lb/MWh) | 1,135 | 1,360 | 1,170 | 950 | 890 | 910 |
| Carbon (lb/MWh) | 310 | 370 | 315 | 260 | 240 | 245 |

* *Electric only, for typical systems under development in 2002. Estimates are based on fuel cell system developers' goals and prototype characteristics. All estimates are for emissions without after-treatment and are adjusted to 15% O₂.*

Source: Energy Nexus Group.

²⁵ Emissions estimates are based on best available data from manufacturers and customer data. Emission expressed in lb/MWh are for electric only performance and do not credit emissions for CHP operations. Typically CHP emissions are calculated by Emissions = (lb emissions/(MWh of Elec generated + (MWh of Heat Recovered/80% Boiler eff)*(ratio of Boiler Regulations/Electric Regulations both in lb/MWh equivalent))) and then compared to the Electric Only Regulations.

²⁶ Conversion from volumetric emission rate (ppmv at 15% O₂) to output based rate (lbs/MWh) for NO_x, CO, and VOC are based on the following conversion multipliers: (0.01418 lb/MWh per ppm NO_x) times (System Elec Efficiency LHV); (0.00977 lb/MWh per ppm of CO) times (System Elec Efficiency, LHV); and (0.00593 lb/MWh per ppm of VOC) times (System Elec Efficiency, LHV) respectively.